

RECENT PROGRESS IN NASA LANGLEY TEXTILE REINFORCED COMPOSITES PROGRAM

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INTRODUCTION

The NASA Langley Research Center is conducting and sponsoring research to explore the benefits of textile reinforced composites for civil transport aircraft primary structures. The objective of this program is to develop and demonstrate the potential of affordable textile reinforced composite materials to meet design properties and damage tolerance requirements of advanced aircraft structural concepts. In addition to in-house research, the program was recently expanded to include major participation by the aircraft industry and aerospace textile companies. The major program elements include development of textile preforms, processing science, mechanics of materials, experimental characterization of materials, and development and evaluation of textile reinforced composite structural elements and subcomponents. The NASA Langley in-house focus is as follows: development of a science-based understanding of resin transfer molding (RTM), development of powder-coated towpreg processes, analysis methodology, and development of a performance database on textile reinforced composites. The focus of the textile industry participation is on development of multidirectional, damage-tolerant preforms, and the aircraft industry participation is in the areas of design, fabrication, and testing of textile reinforced composite structural elements and subcomponents.

Textile processes such as 3-D weaving, 2-D and 3-D braiding, and knitting/stitching are being compared with conventional laminated tape processes for improved damage tolerance. Through-the-thickness reinforcements offer significant damage tolerance improvements. However, these gains must be weighed against potential loss in in-plane properties such as strength and stiffness. Analytical trade studies are underway to establish design guidelines for the application of textile material forms to meet specific loading requirements. Fabrication and testing of large structural components are required to establish the full potential of textile reinforced composite materials. The goals of the NASA Langley-sponsored research program are to demonstrate technology readiness with subscale composite components by 1995 and to verify the performance of full-scale composite primary aircraft structural components by 1997.

TEXTILE REINFORCED COMPOSITES

- RESEARCH TEAM -

The team that has been assembled to conduct research on textile reinforced composites is shown in figure 1. The current team includes NASA Langley in-house personnel, numerous universities, textile fabricators, and major aerospace contractors. The team will expand to meet program needs as required. Recent program emphasis has been on development of aircraft quality textile preforms, development of science-based processes, development of mechanics methodologies, and experimental characterization of textile reinforced composite materials. As these technologies mature, future emphasis will shift to design, analysis, fabrication, and test of structural elements and subcomponents. The recent addition of Lockheed to the team and the redirection of Grumman will provide a much needed aircraft structures focus to the textile reinforced composites program.

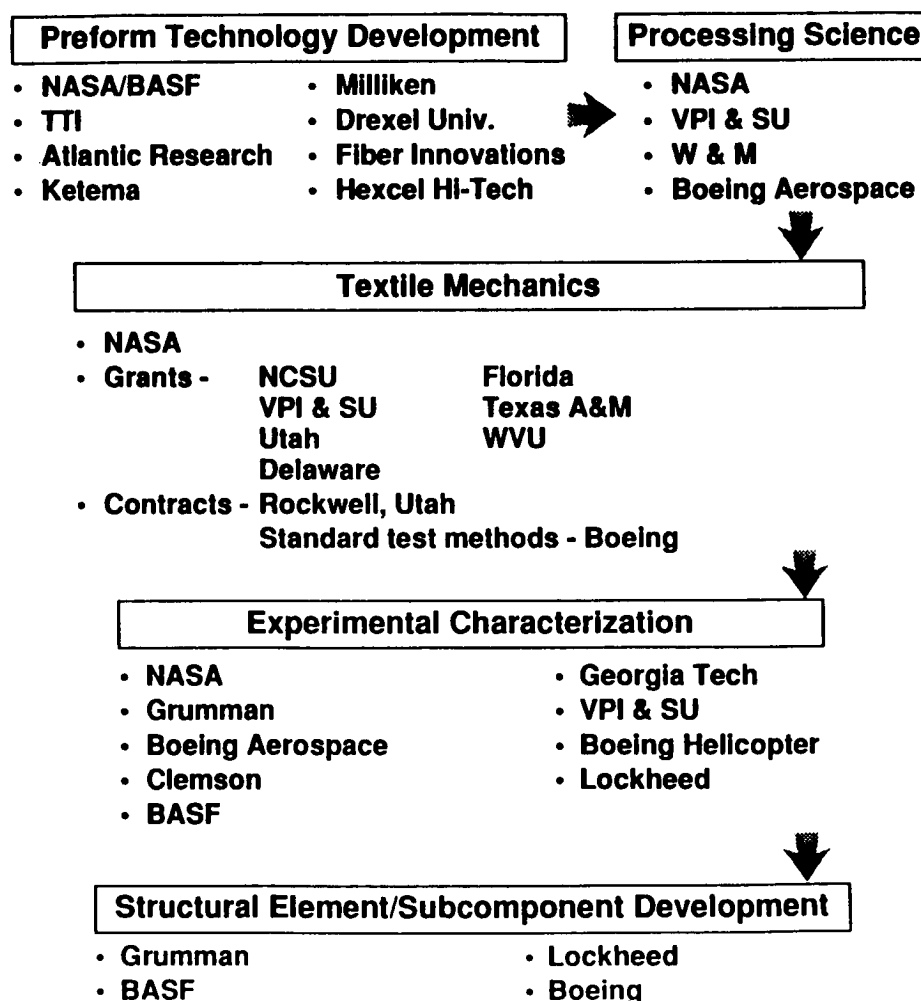


Figure 1

ACT CONTRACTS FOCUSED ON TEXTILE REINFORCED COMPOSITES

The four Advanced Composites Technology (ACT) contracts that are focused on textile reinforced composites are summarized in figure 2. The Lockheed Aeronautical Systems contract is focusing on the application of textile materials to aircraft fuselage structures. Textile preforms, RTM and powdered epoxy resins, and innovative tooling concepts will be developed for four types of fuselage structural subcomponents. Included will be circumferential frames, window-belt insert, keel beam/frame intersection, and crown panels. Composite subcomponents will be tested at Lockheed, NASA Langley, and Boeing Commercial Airplane Co.

The Grumman contract is focusing on cross-stiffened integrally woven fuselage elements and lower side quadrant fuselage panels. The evaluation of integrally woven wing Y-spars has been completed. In addition, Grumman will focus on developing design guidelines and analysis methods for through-the-thickness reinforced composite structural elements. The Rockwell contract is focusing on the fatigue response of woven composites. Experiments are being conducted and micromechanics models are being developed to characterize damage initiation and growth. Strength and fatigue life prediction methods are also being developed for textile reinforced composites.

The BASF contract is focusing on commingled thermoplastic/carbon yarns and powder-coated towpreg for fabrication of woven and braided structural elements. Innovative tooling concepts and fabrication studies will be conducted for woven and braided panels. The powder-coated towpreg process is in its early stages of development. BASF will investigate scale-up feasibility for production of large quantities of powder-coated towpreg. Towpreg characteristics will be optimized to achieve cost-effective preform fabrication in conventional weaving and braiding machines.

Lockheed Aeronautical Systems	Grumman Aircraft Systems
• Preform development and processing • RTM and powdered epoxy resins • Innovative tooling and fab. development • Circumferential fuselage frames • Fuselage window-belt insert • Keel beam/frame intersection • Fuselage crown panel • Design/analysis methodology	• Design guidelines/analysis methods • Integrally woven wing Y-spar • Cross-stiffened integrally woven fuselage element • Lower side quadrant fuselage panel
Rockwell International	BASF Structural Materials
• Static and fatigue response of woven composites • Micromechanics models of damage initiation and growth • Strength and fatigue life prediction methodologies	• Commingled thermoplastic/carbon yarns • Powder-coated towpreg • Weaving and braiding studies • Tooling and consolidation studies for woven panels and braided frames • Scale-up of towpreg and composite processing

Figure 2

TEXTILE MATERIAL FORMS OF INTEREST

Textile material forms that have the most potential for primary aircraft structural applications are indicated in figure 3. The ultimate goal is to minimize the number of individual plies required to build-up part thickness. Integral weaving and braiding will result in near-net structural shapes that require only minimal machining and fastening. Multilayer-multiaxial knitted fabrics are being investigated as a cost-effective replacement for biaxial woven broadgoods. The knitted fabrics can be postformed to achieve selected structural shapes. If high concentrations of 0-degree reinforcements are required, low crimp uniweave fabric can be added to woven, knitted, or braided material forms. Through-the-thickness stitching has been used to provide improved out-of-plane strength, damage tolerance, and delamination resistance. It is expected that continued developments in automation of textile processes will result in significant cost savings in fabricating textile preforms for aircraft structures.

- **Low crimp uniweave fabric**
- **Integrally woven fabric shapes (2-D, 3-D)**
- **Multiaxial knitted fabric (0, 90, $\pm\theta$)**
- **Braided preforms (2-D, 3-D, interlock)**
- **Stitched combinations of woven, knitted and braided preforms**

Figure 3

TEXTILE MATERIALS BEING EVALUATED

The textile materials that are currently being investigated in the NASA Langley program are shown in figure 4. Quasi-isotropic (+45, 0, -45, 90) multiaxial warp knit fabrics have been produced by Hexcel Hi-Tech and Milliken. Tests are underway to assess performance differences between 3, 6, and 12K tows. Kevlar and polyester knitting yarns and Kevlar and carbon stitching yarns are being investigated. Triaxial (0 ± 30) braids produced by Fiber Innovations are currently being evaluated. Both stitched and unstitched materials are being tested. Atlantic Research has produced 3-D braids for improved impact resistance. Several different 3-D interlock weave configurations have been produced by Textile Technologies, Inc. All of these materials are being tested to assess mechanical properties and impact damage tolerance.

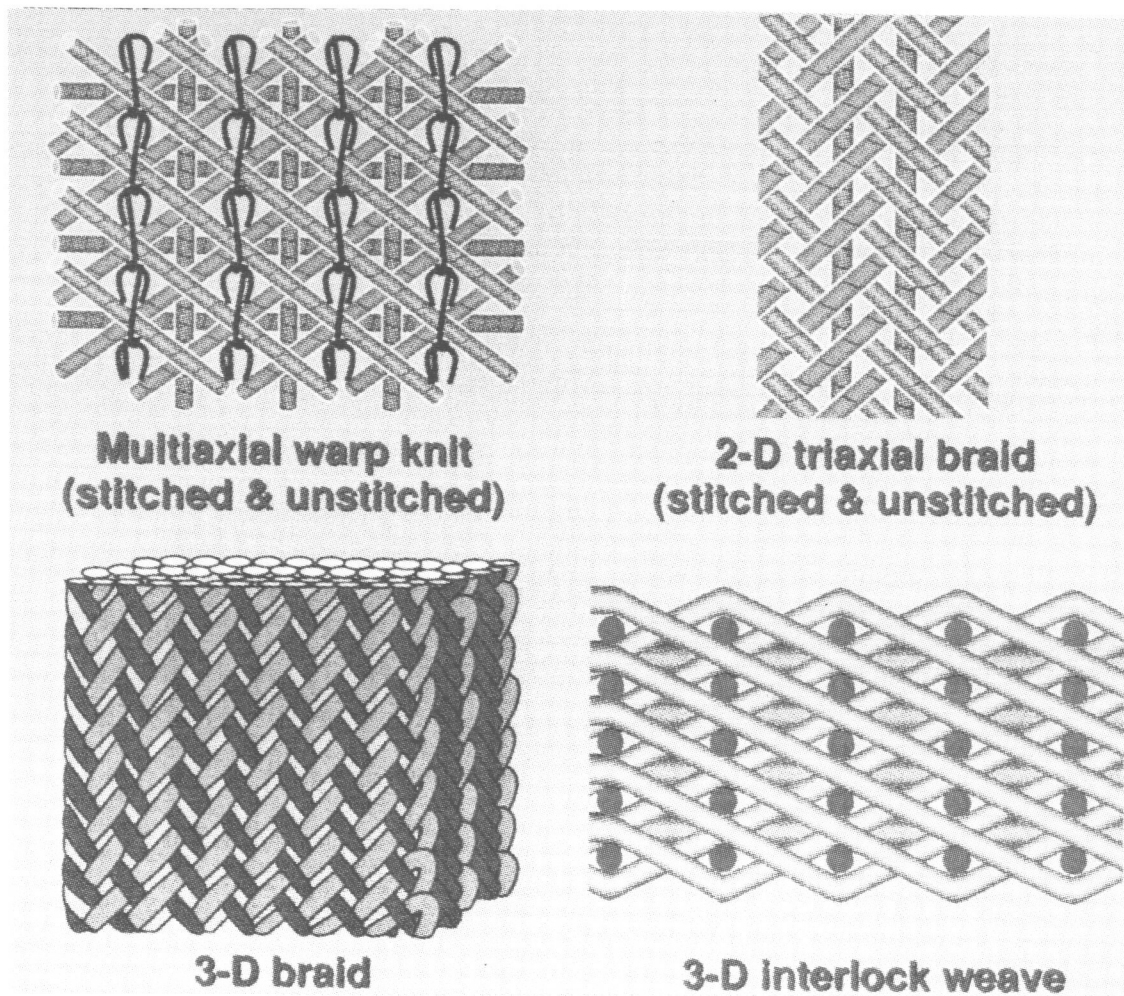


Figure 4

NET-SHAPED TEXTILE PREFORMS

Some of the textile preforms that are being considered for structural applications are shown in figure 5. Weaving is well-suited for production of stiffened panels. However, automated weaving processes are currently limited to (0/90) fiber orientations in the skin and stiffening elements. Off-axis reinforcement, if required, must be bonded or stitched onto the surfaces of the (0/90) preform. Two-dimensional multilayer braiding is being used to produce complex curved shapes such as fuselage frames. The braiding process provides multidirectional fiber continuity throughout the preform structural shape. Both 2-D and 3-D braiding processes can produce structural shapes that are difficult or inefficient to achieve by other processes.

The knitted sine wave beam shown in figure 5 was produced by postforming knitted fabric to a specified shape. Epoxy powder tackifiers or stitching can be used to tack layers together. The integrally woven Y-spar shown in figure 5 can be produced in continuous lengths. As with the hat-stiffened panel, off-axis reinforcement must be added to the spar as a secondary operation.

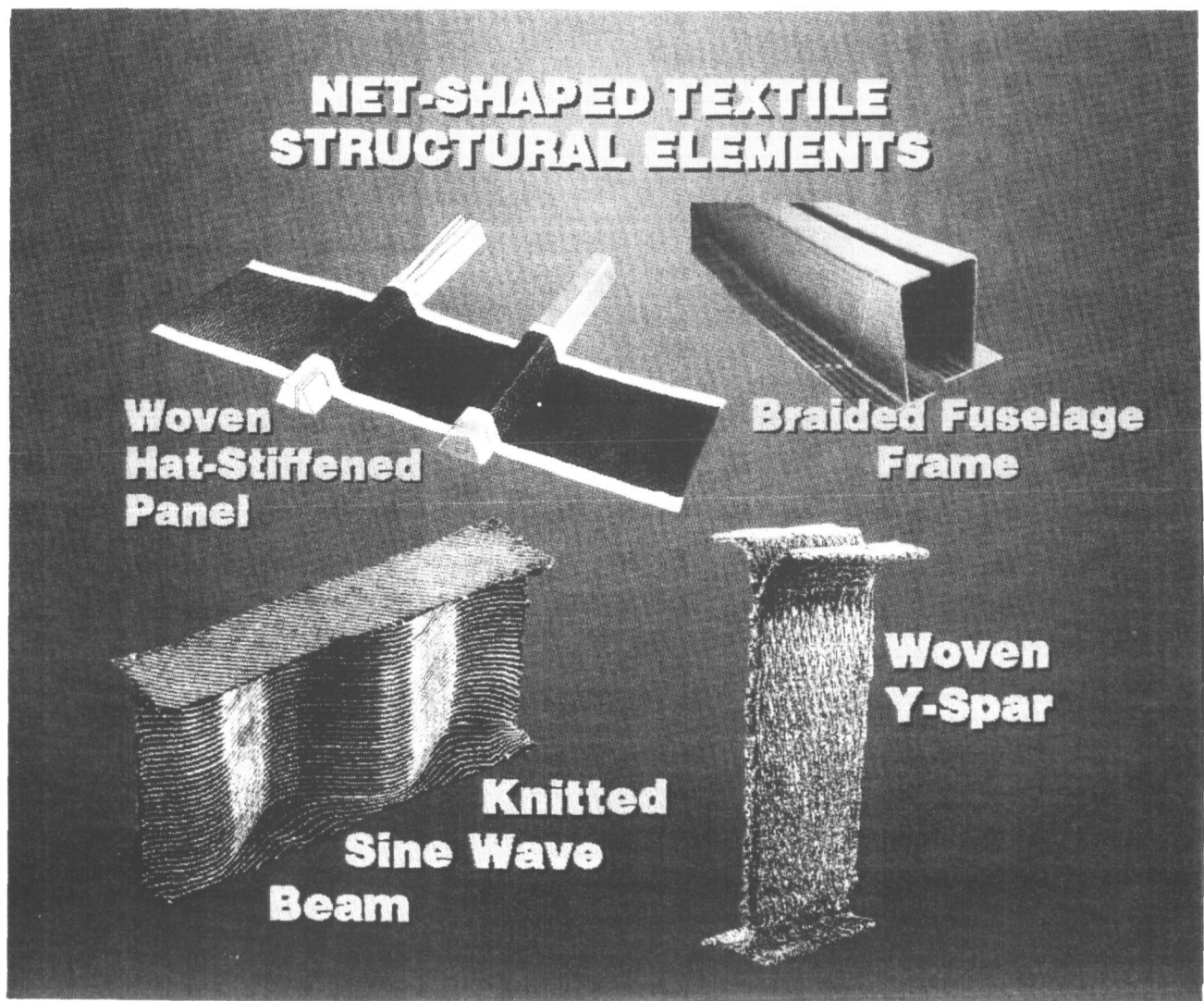


Figure 5

COST-EFFECTIVE PROCESSES AND FABRICATION METHODS

Cost-effective processes and fabrication methods must be developed to produce cost-competitive aircraft-quality composite structures from the preforms discussed previously. The objectives and program elements for this research are shown in figure 6. Two major areas of research focus are resin transfer molding (RTM) and powder-coated towpreg. RTM is one of the most promising processes to achieve cost-effective structures because it uses resins and fibers in their lowest cost form. RTM has been used for many years but previous applications did not have stringent performance requirements. New resins with enhanced flow properties, higher strength, and improved toughness are currently under development. Appropriate tooling concepts must be developed to make cost-effective use of RTM. Analytical models are being developed to understand the RTM process and to eliminate trial-and-error procedures that are commonly used.

Powdered resins are a potential alternative to RTM. Powder-coated tows, if properly prepared, can be used in textile processes such as a weaving and braiding. Hence, pumping of resin into the preform, as with RTM, can be eliminated. The powder coating process is in its infancy and significant research is required before aircraft-quality composite structures can be produced. The research program elements shown in figure 6 are currently being pursued by NASA Langley, aerospace contractors, and universities.

- **Objectives**
 - **Develop innovative processes and tooling concepts for RTM**
 - **Optimize powder coating techniques, demonstrate weaving and braiding characteristics, and develop fabrication processes**
- **Program elements**
 - RTM**
 - **Improved RTM resins with high modulus, strength and toughness**
 - **Analytical processing science models for liquid, semi-solid and paste resins**
 - **Innovative compaction and tooling concepts for structural elements**
 - Powdered resins**
 - **Optimized powder coating techniques**
 - **Weaving and braiding trials**
 - **Fiber wet-out and preform consolidation models**
 - **Tooling concepts for complex structural shapes**
 - **Technology demonstration through structural element fabrication**

Figure 6

PROCESSING SCIENCE OF TEXTILE REINFORCED COMPOSITES

Science-based processing studies are underway for textile reinforced composites. Analytical and experimental studies are being conducted to characterize preform and resin behavior for RTM. Major program elements are shown in figure 7. To model the RTM process, preform properties such as permeability and compaction, and resin viscosity as a function of temperature and time, must be known. Experimental studies are underway to determine preform permeability and compaction coefficients as a function of preform architecture. Resin infiltration studies are underway to predict how various resins flow through porous fiber preforms. Infiltration is affected by preform porosity, resin viscosity, flow direction, and applied pressure. Once the preforms are infiltrated, a cure kinetics analysis is performed to predict the degree of cure. A finite element analysis that utilizes preform and resin characteristic data has been employed to predict initial resin mass required, resin front position and time required for preform infiltration, resin viscosity and degree of cure, and final part thickness and fiber volume fraction.

Dielectric sensors are being used to track resin behavior as a function of time and to verify the RTM simulation model discussed above. The sensors can monitor infiltration position, resin viscosity, and degree of resin cure. The in-situ sensors can be used for real-time feedback control so that processing parameters can be modified if required. Flow visualization studies will be conducted to verify flow front position and to substantiate sensor output.

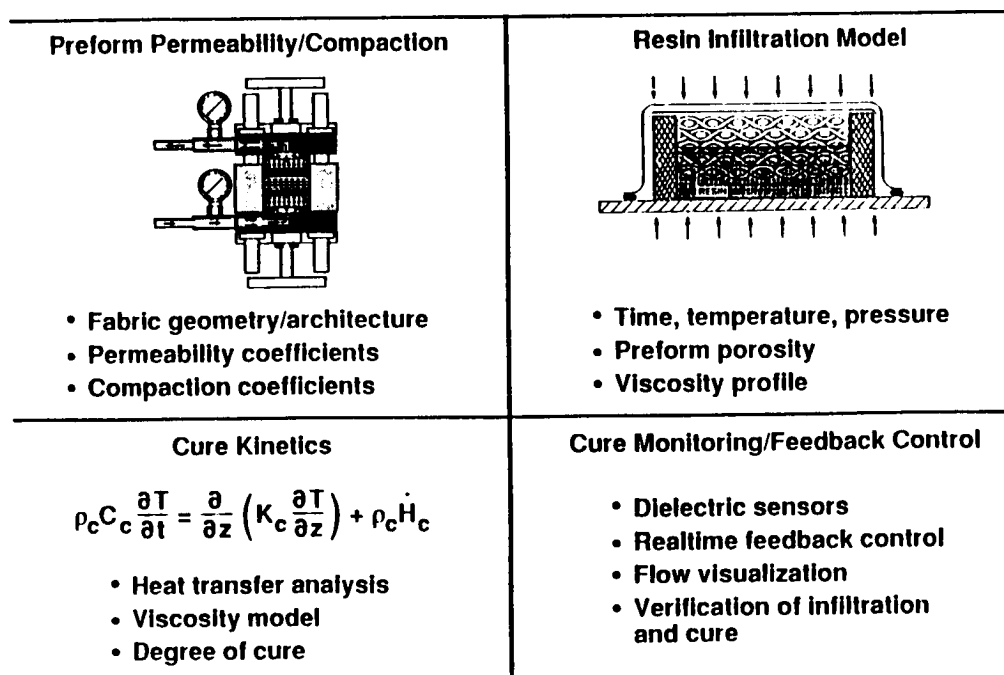


Figure 7

COMPACTION AND PERMEABILITY CHARACTERISTICS OF HEXCEL HI-TECH KNITTED FABRIC

An important part of resin transfer molding textile material forms is understanding the compaction and permeability characteristics of the material. Compaction and permeability coefficients can be used to predict fiber volume fraction and ease of resin infiltration. As shown in figure 8, fiber volume fraction and fabric thickness are nonlinear functions of compaction pressure. The Hexcel Hi-Tech knitted fabric had a nominal uncompacted fiber volume fraction of approximately 37 percent and a thickness of approximately 0.39-inch. To achieve a fiber volume fraction of 60 percent and a final thickness of 0.250-inch, a compaction pressure of approximately 35 psig is required.

Also shown in figure 8 is the effect of fiber volume fraction on permeability. Permeability is a function of fabric architecture, compaction, porosity, and fluid flow direction. Permeability along a fiber bundle can be an order of magnitude greater than transverse to the fiber bundle. Permeability for the Hexcel knitted fabric is approximately 5 in² for a fiber volume fraction of 60 percent. At a fiber volume fraction of 50 percent, the fabric would be much easier to infiltrate at a permeability of 14 in².

(+45/0/-45/90)_{2s}

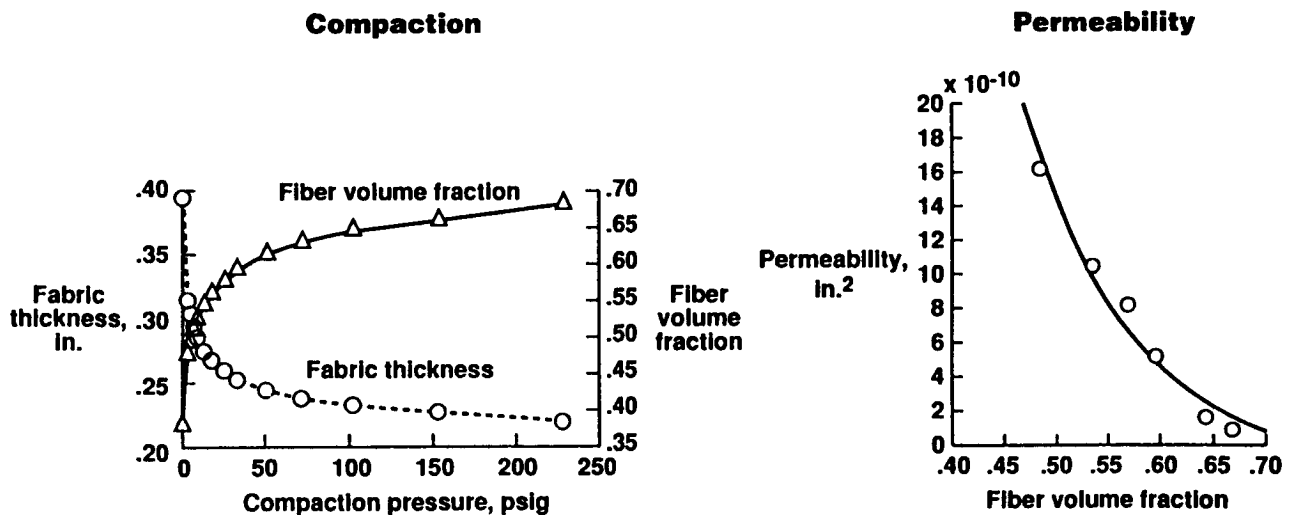


Figure 8

POWDER-COATED TOWPREG TECHNOLOGY FOR TEXTILE REINFORCED COMPOSITES

As indicated in figure 9, the objective of powder-coated towpreg research is to investigate the viability of powder coating as an alternate to RTM for fabrication of textile reinforced composites. To achieve this objective, the approach shown in figure 9 is being followed. First generation powder-coated towpreg is currently being woven into flat panels to evaluate mechanical properties and damage tolerance. Stiffened panels will be evaluated to address fabrication issues and to assess structural performance. After weaving trials are completed, braiding studies will be conducted to assess other textile processing methods. On a continuing basis, processing studies will be conducted at the powder application level to optimize application techniques. Processing science studies will be conducted to understand compaction and consolidation issues specific to particular fiber forms and types of powder.

- **Objective:**
 - **Develop powder-coated towpreg technology as a viable alternate to RTM for fabrication of textile composites**
- **Approach:**
 - **Verify weave capability of powder-coated towpreg by systematically fabricating and evaluating flat composite panels of increasing complexity**
 - **Verify braid capability of powder-coated towpreg by fabricating and evaluating braided flat composite panels**
 - **Fabricate and evaluate single and three-stringer panels from powder-coated towpreg**
 - **Conduct process optimization studies to determine the important physical properties and processing characteristics of powder-coated towpreg**
 - **Conduct detailed compaction/consolidation studies to determine the proper fabrication procedures for preforms made from powder-coated towpreg**

Figure 9

POWDER-COATED TOWPREG TECHNOLOGY FOR TEXTILE REINFORCED COMPOSITES

- RESEARCH TEAM -

The research team that has been assembled to conduct research on powder-coated towpreg technology is shown in figure 10. NASA Langley is conducting in-house research and is sponsoring grant and contract research to advance powder-coated towpreg technology. Powders are being developed by 3M, Dow, Shell, and Mitsui Toatsu Chemicals. Basic powder application technology is being developed by Old Dominion University research associates at NASA Langley, Georgia Institute of Technology, and Clemson University. BASF Structural Materials is focusing on optimizing the towpreg process and processing scale-up for production quantities of towpreg. NASA Langley and BASF are sponsoring weaving and braiding studies to produce aircraft quality textile preforms. The textile companies that are currently involved in the program include Textile Technologies Inc., Fabric Development, J. B. Martin, and Fiber Innovations.

As part of the Lockheed ACT contract refocus, weaving and braiding will be investigated for fabrication of aircraft fuselage structural elements such as curved frames and stiffened panels. Powder-coated towpreg structural elements will be compared with similar elements fabricated with RTM processes.

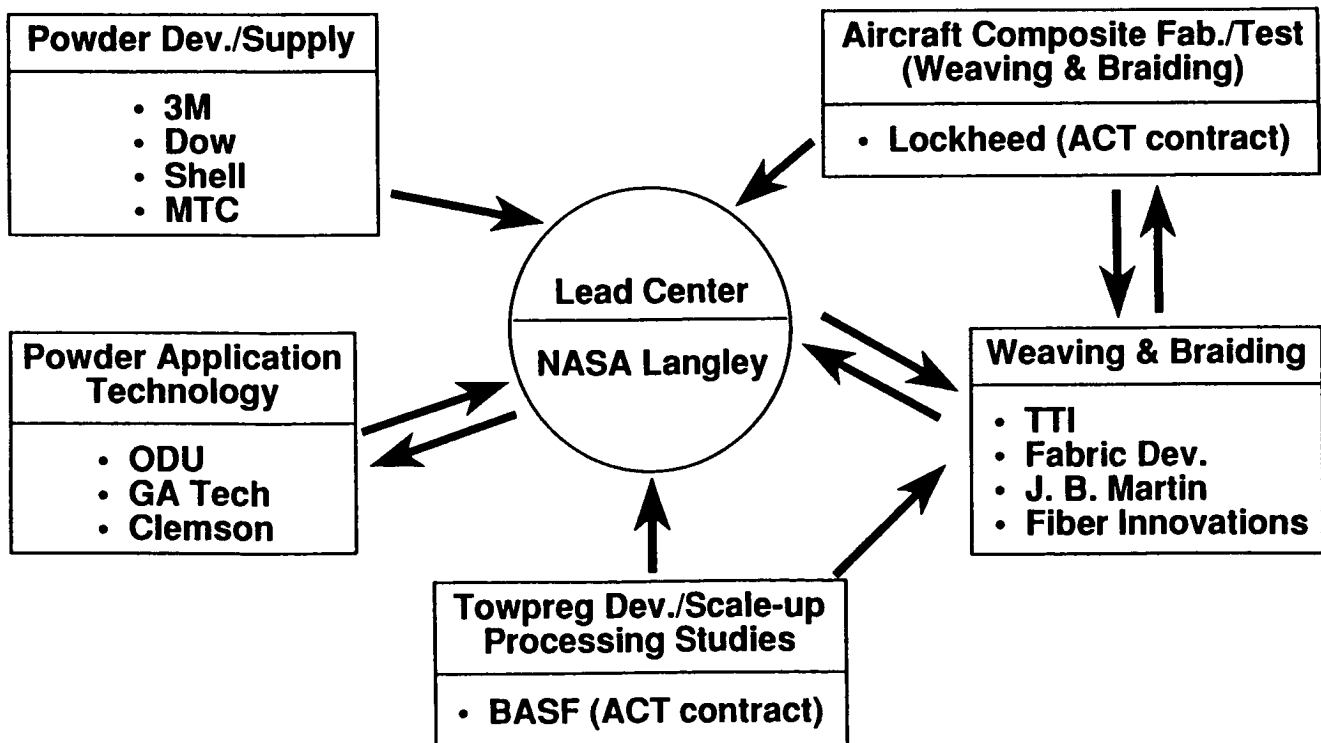


Figure 10

NASA LARC ADVANCED POLYMER POWDER TOWPREG FACILITY

The powder-coated towpreg facility that is operational at NASA Langley Research Center is shown in figure 11. The experimental system is composed of five components: (1) fiber feed with tension brake, (2) air jet tow spreader, (3) fluidization/ polymer deposition chamber, (4) electric heater for polymer fusion onto tow bundles, and (5) towpreg take-up with tow speed and twist control. The LaRC facility operates routinely at line speeds up to 30 ft./min. Both 3K and 12K carbon tows have been coated successfully with the NASA LaRC system.

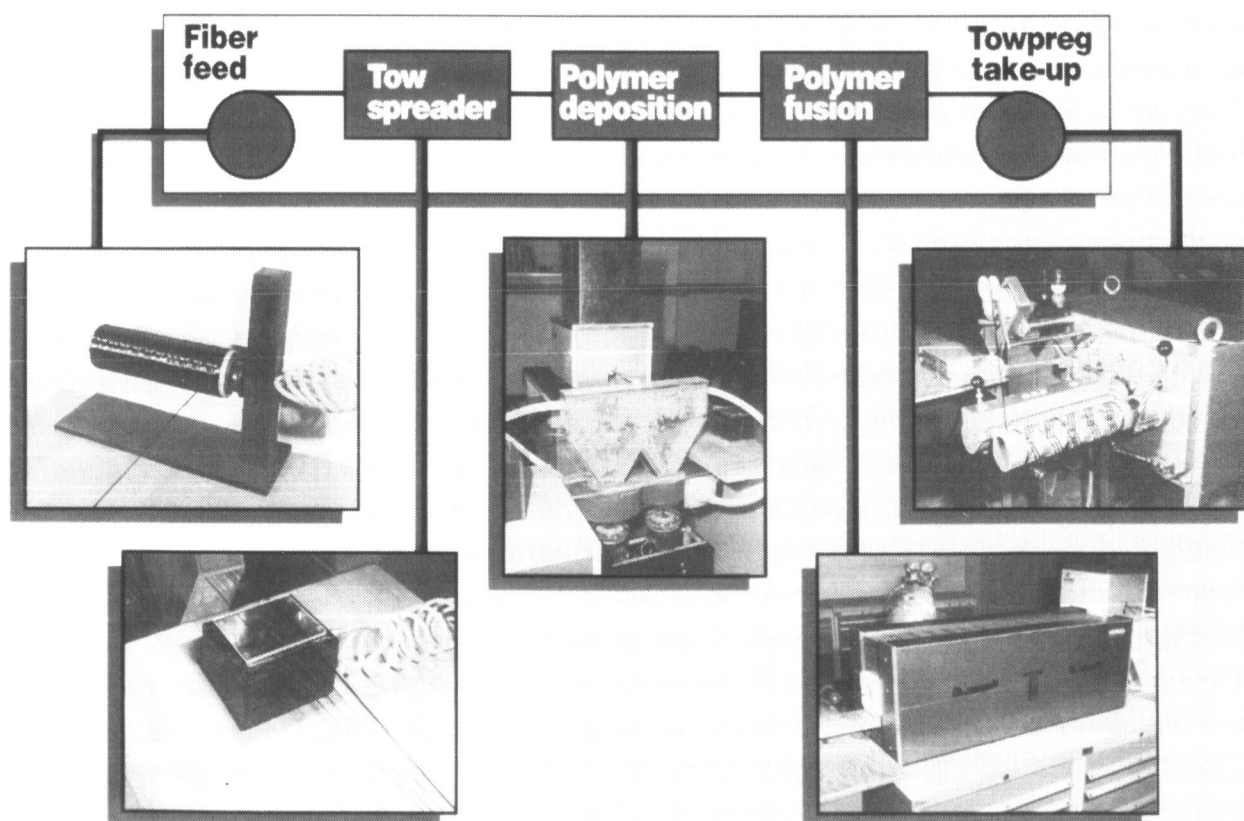


Figure 11

IMPORTANT FEATURES OF THE POWDER COATING PROCESS

The dry powder coating process under development at NASA LaRC overcomes many of the difficulties associated with melt, solution, and slurry prepregging. Some of the important features of the powder coating process are shown in figure 12. The process is versatile in that it is applicable to thermoplastic and thermoset matrix materials. The powder application process operates at room temperature and no solvents are required. Since refrigeration is not required, the powders do not have "out-time" problems that are inherent with state-of-the-art prepreg. As a result, less waste and spoilage should be a significant benefit for powder-coated towpreg. Preliminary engineering studies indicate that powder-coated towpreg can be used in conventional textile processes. Significant research is currently underway to demonstrate that the powder process is a viable alternative to RTM processing of textile reinforced composites.

- **Versatile: Thermoplastics and thermosets**
- **Operates at room temperature**
- **No solvents involved**
- **Manageable exposure to toxic materials**
- **Prepreg requires no significant refrigeration:
reduces waste/spoilage**
- **Prepreg can be woven, filament wound, pultruded,
thermoformed**
- **Viable alternative to RTM processing of textile
preform composites**

Figure 12

POLYMER POWDER RESEARCH

Some of the powders and product forms that are being investigated in the NASA LaRC program are listed in figure 13. Five different epoxy powders and two polyarylene ether powders are being investigated for subsonic commercial transport applications. Several polyimide and bismaleimide powders are being considered for application to future high-speed civil transport aircraft. The uniformity of powder deposition is indicated in the photograph of powder prepreg. Eight harness satin fabric that was woven with powder-coated towpreg is shown in the lower left of figure 13. Processing/consolidation studies are underway with this fabric. Mechanical properties will be compared with properties obtained with conventional prepreg fabric.

Some of the powder-coated product forms that are being investigated include uniweave prepreg tape, woven broadgoods, 2-D/3-D woven and braided textile preforms, and towpreg ribbon for use in advanced tow placement machines.

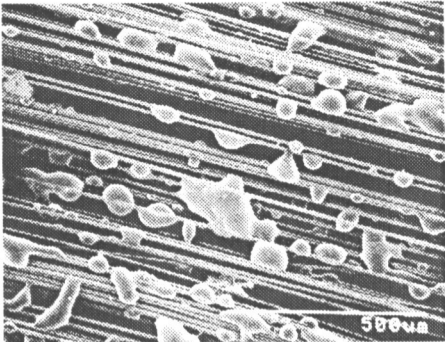
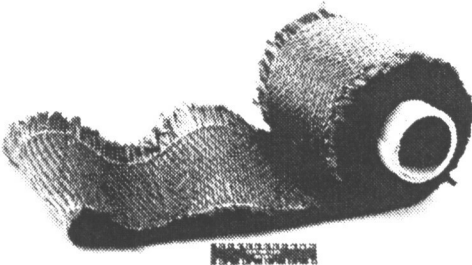
Powder Resins	Powder Prepreg
Epoxies: CET-2 (Dow) CET-3 (Dow) RP-500 (3M) High Tg (3M) RSS1952 (Shell) Polyarylene ethers: PEEK (ICI) PEKK (DuPont) Polyimides: LaRC-TPI (MTC) PMR-15 & Mods (LaRC) New-TPI (MTC) Bismaleimides: TBD (Shell)	
Woven Powder Towpreg	Product Forms
	• Uniweave prepreg tape • Woven broadgoods • 2-D/3-D woven and braided textile preforms • Towpreg ribbon for advanced tow placement

Figure 13

LONGITUDINAL FLEXURE STRENGTH AND MODULUS OF POWDER-COATED TOWPREG UNIDIRECTIONAL LAMINATES

Longitudinal flexure strength and modulus data for unidirectional composites fabricated with four different powders are shown in figure 14. Flexure strength ranges from 256 ksi for the LaRC TPI material to 300 ksi for the Shell RSS-1952 material. Flexure modulus ranges from 17.5 Msi for the 3M PR-500 material to 18.7 Msi for the Dow CET-2 material. These results for powder-coated G30-500 carbon fiber are similar to results expected for conventional preimpregnated tape materials. The results shown in figure 14 are normalized to a fiber volume fraction of 0.60.

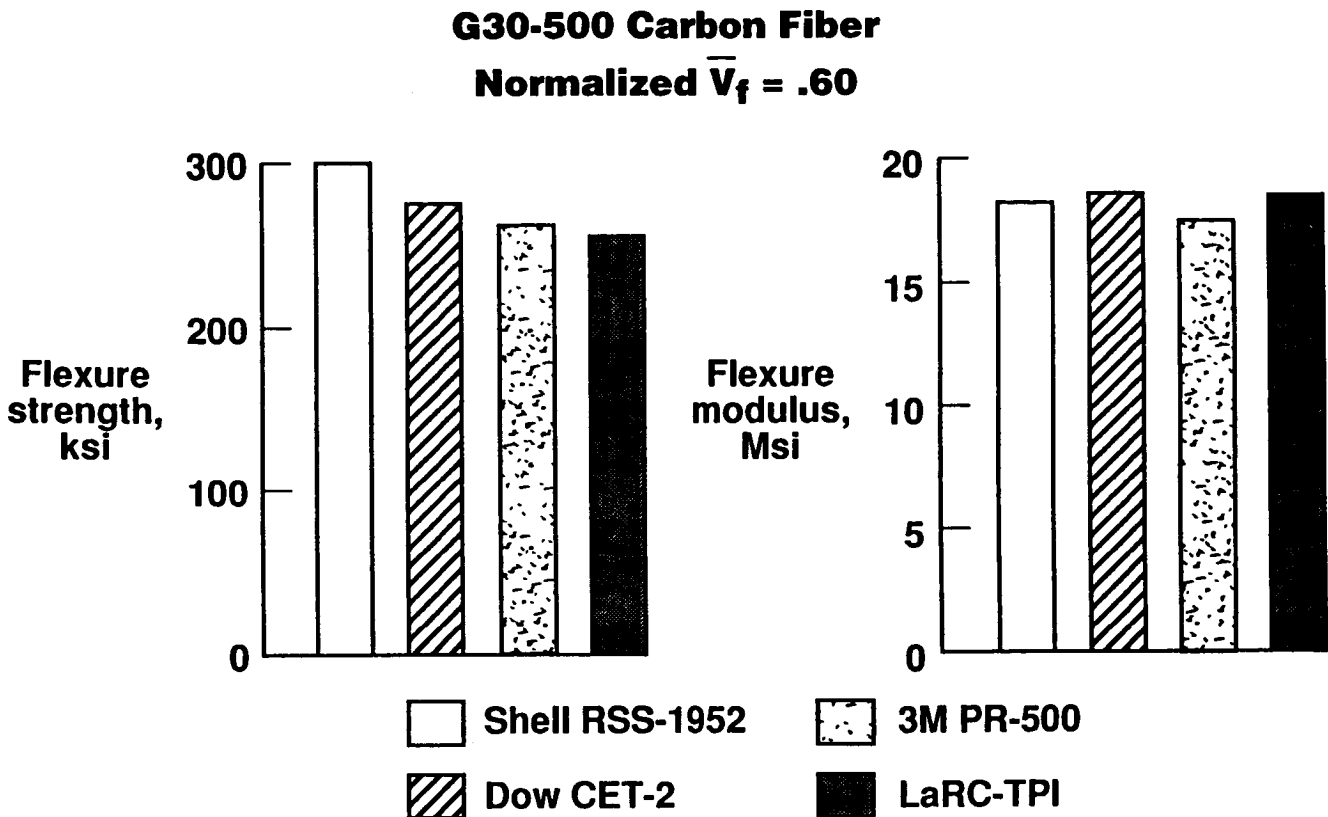


Figure 14

POWDER-COATED TOWPREG WEAVING STUDIES

Weaving studies are underway to determine powder-coated towpreg characteristics that will allow the towpreg to be woven on conventional looms. An outline of the weaving studies is shown in figure 15. During powder application, the following towpreg characteristics must be considered: degree of powder adhesion, tow flexibility, tow dimensional tolerance, tow twist, and damage during the coating process. All of these factors can affect the quality of woven product forms. Some of the weaving parameters that may require attention include loom/equipment modifications to accommodate towpreg, loom speed, tow abrasion/powder loss, and tow damage as a result of weaving operations.

The textile architectures that are being considered include 2-D uniweave and satin weaves, 3-D layer-to-layer interlock, and 3-D net-shape preforms. Once high-quality fabrics are achieved, processing studies must be conducted to arrive at optimum composite properties. One concern is the uniformity in resin content throughout the woven preform. Other issues such as towpreg bulk factor and compaction must be addressed. These issues are related to tool designs that will produce well-consolidated composites. Processing science studies will be conducted to aid in cure cycle development and to minimize the time required to arrive at optimum processing conditions.

Towpreg Characteristics	Weaving Parameters
• Degree of powder adhesion • Tow flexibility • Tow dimensional tolerance • Tow twist • Damage during coating process	• Loom/equipment modifications required to accommodate towpreg • Loom speed • Tow abrasion/powder loss during weaving • Tow damage during weaving
Textile Architectures	Processing Technology
• 2-D Uniweave • 2-D Satin weaves • 3-D Layer-to-layer interlock • 3-D Net shape preforms	• Optimum resin content • Towpreg bulk factor/compaction • Tool design/composite consolidation • Processing science/cure cycle development

Figure 15

MECHANICS OF MATERIALS MODELS FOR TEXTILE COMPOSITES

NASA Langley has assembled a team of mechanics experts to develop methodologies and models to predict performance of textile reinforced composites. The major program elements are outlined in figure 16. An accurate description of the fiber architecture is required to adequately predict mechanical response. Mathematical formulations are being developed to describe yarn path and geometry of repeating unit cells. Stress-strain relationships will be developed from the homogeneous or continuum mechanics viewpoint. The upper right schematic in figure 16 illustrates a strategy that is mathematically similar to the finite element discretization method. Master subcells that reflect the essence of the repeating geometry are arranged in the pattern necessary to model the unit cell. The stiffness matrix for the unit cell is computed by standard matrix manipulations of the stiffness matrices of the master subcells. This type of model may be used to directly define the A, B, D coefficients or to calculate effective elastic moduli by imposing the correct boundary conditions on the unit cell.

Continuum level strength models will be developed in conjunction with the stress-strain models. This will allow a first approximation of load carrying capacity to be obtained from the average stresses computed by a global structural analysis using the homogenized stiffness properties. The average stresses will then be evaluated in a tensor polynomial failure criterion, for example, using phenomenological strength parameters determined from simple coupon tests.

A methodology will be developed to predict damage progression and residual strength using global/local analysis strategies to address damage tolerance requirements. Initial emphasis will be on modeling impact damage. Fatigue behavior will be experimentally characterized and then treated analytically. Fatigue life prediction methodologies will be developed for in-plane tension and compression loads and for out-of-plane loads.

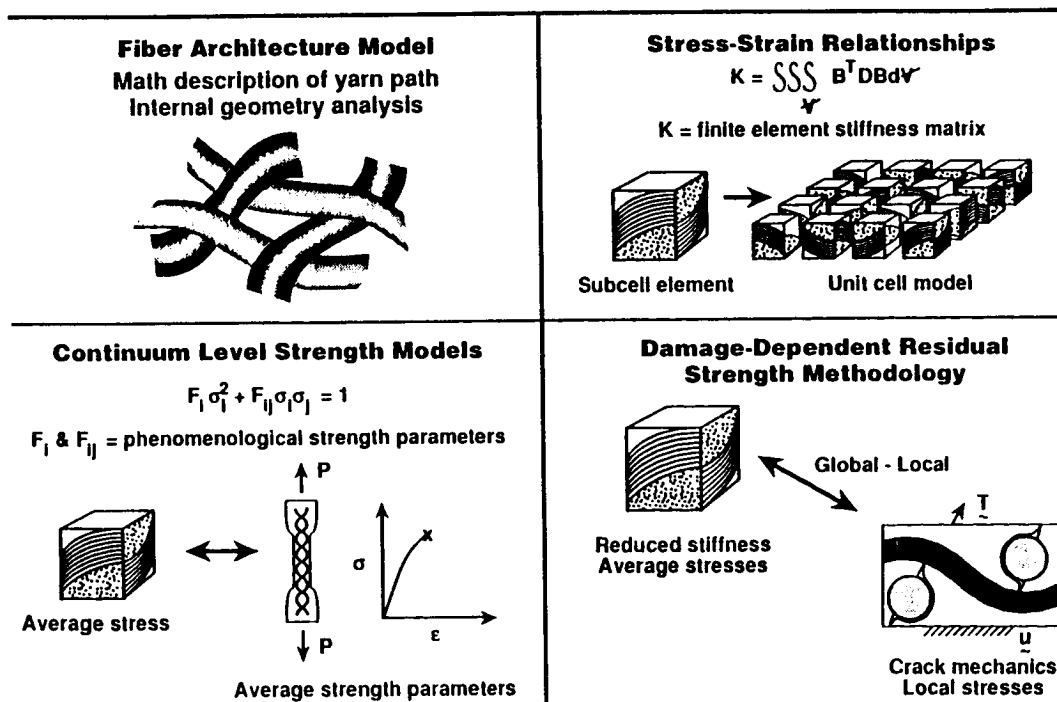


Figure 16

TEXTILE MECHANICS

- RESEARCH TEAM -

The Mechanics of Materials Branch (MEMB) at NASA Langley has the lead role in developing mechanics methods for performance prediction of textile reinforced composites. A "textile mechanics working group" has been formulated to ensure program coordination and cooperation among the participants in a synergistic environment. The working group is comprised of the MEMB in-house research team, all program contractors and grantees, and ACT contract representatives from Lockheed, Grumman, Douglas, and Boeing. The working group meets quarterly for 1- or 2-day informal work-in-progress reviews. Co-location of team members at NASA Langley for various periods of time is encouraged to facilitate technology transfer.

The research topics that are currently being addressed are indicated in figure 17. Fiber architecture math models are being developed at North Carolina State University. Stiffness and strength models for stitched laminates are being developed at the University of Florida. Global/local analysis methodologies and fatigue response of braided composites are being developed at Virginia Polytechnic Institute and State University. Notch effects in braided composites are being studied at West Virginia University.

The Rockwell Science Center is conducting research on impact and fatigue response of 3-D woven fabrics and knitted/stitched materials. The University of Utah is studying failure of textile reinforced composites under combined stress states. Texas A&M University is focusing on micromechanics analysis of compression failure in textile materials. The University of Delaware is conducting a design study for an out-of-plane strength test specimen. Development of standard test methods will be discussed in a subsequent figure.

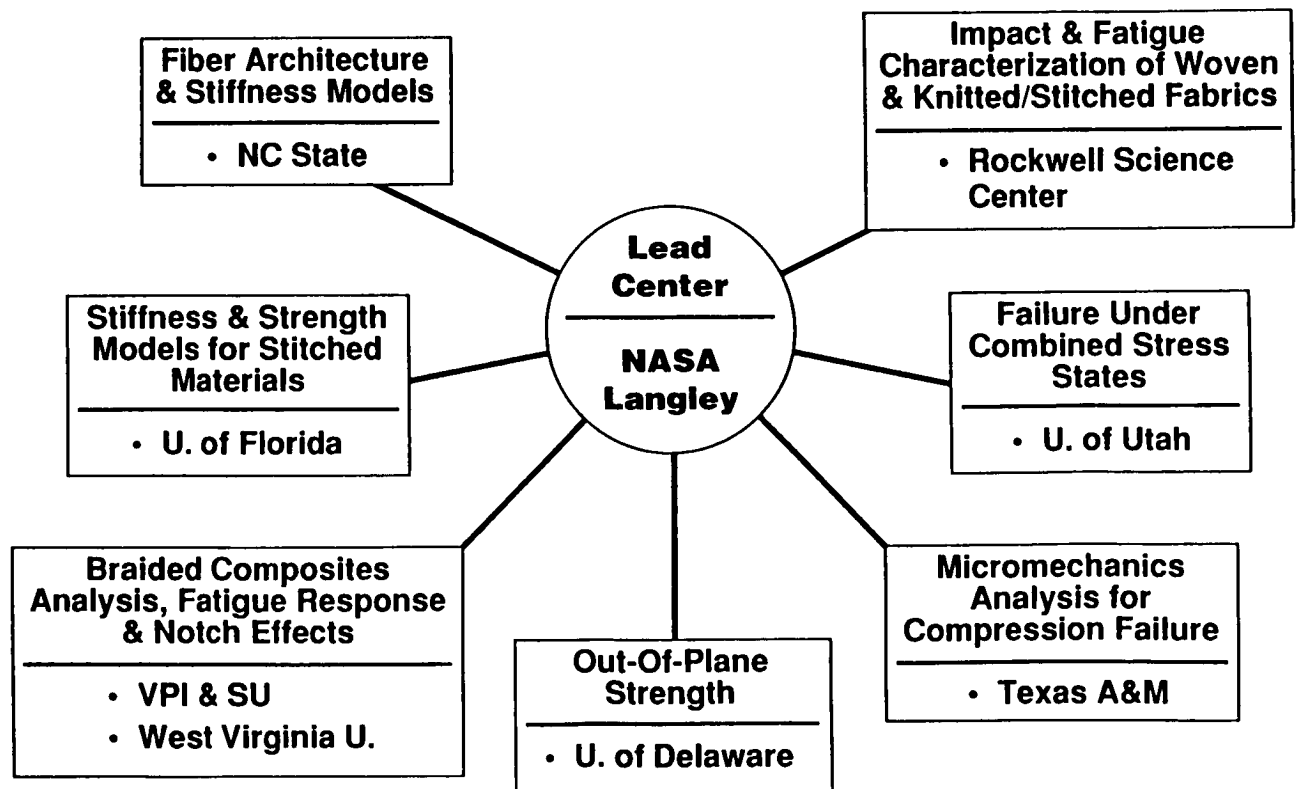


Figure 17

TEXTILE FIBER ARCHITECTURE MODEL

In order to perform an accurate stress analysis of textile reinforced composites, the textile fiber architecture must be accurately defined. One approach that is being studied is shown in figure 18. First, models of the yarn path must be formulated. The reinforcing structure is modeled as a set of fixed points in space that represent the position of the center of the yarn. These points are "hard points" in that they are determined by the manufacturing process. In order to develop a realistic model of the yarn as it moves through space, the center-line points are smoothed with a B-spline to create a minimal strain energy curve. The cross-sectional shape of the yarn is then swept along this smoothed center-line, maintaining appropriate bending and twisting. The surface is then constructed by applying a Bezier patch to the surface points generated from this sweep. The resulting model represents the surface of the yarns within the fibrous structure.

The second step is to conduct an internal geometric analysis of the fiber architecture. The yarns are sectioned numerically to compute yarn orientations and cross-sectional areas. These mathematical models must be validated and adjusted as necessary by comparing with photomicrographs of the consolidated composite. Once the geometric model is verified, the mathematical description of the architecture can be applied to various analytical techniques, ranging from homogenization to detailed finite element approaches.

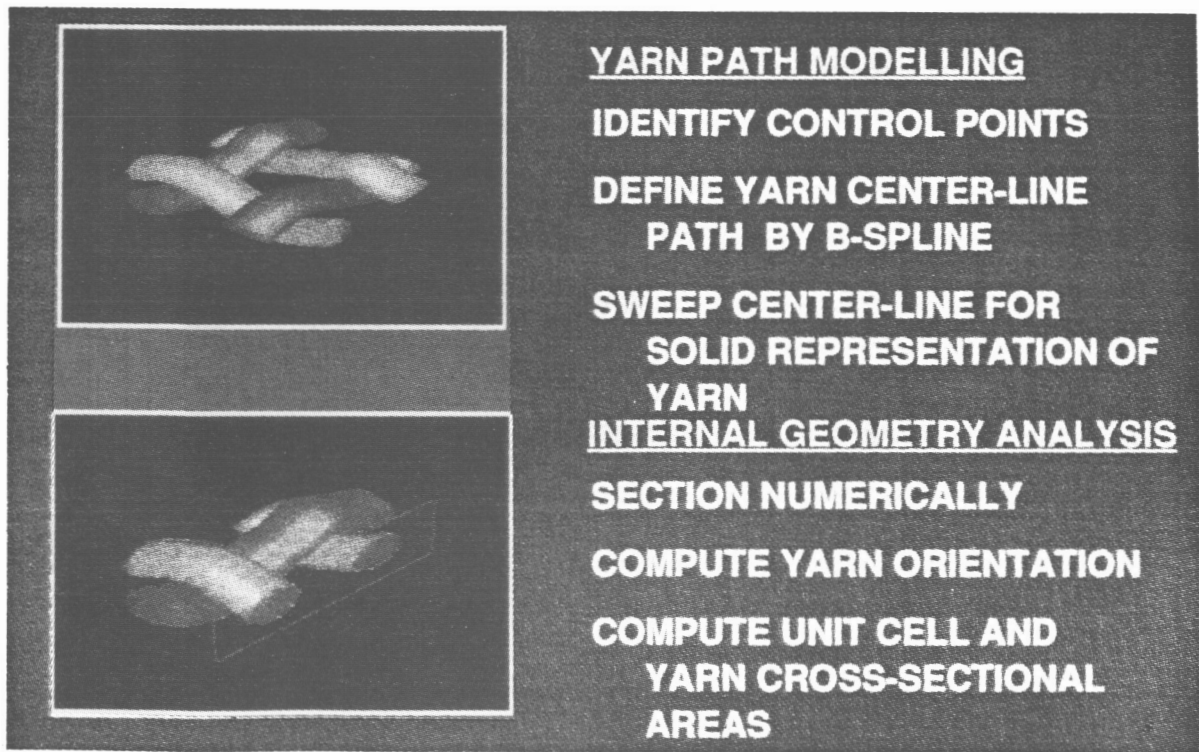


Figure 18

EXPERIMENTAL CHARACTERIZATION AND PRELIMINARY DESIGN PROPERTIES

An experimental characterization program is underway at NASA Langley to develop mechanical properties, damage tolerance, and preliminary design properties for textile reinforced composites. The objectives and program elements are shown in figure 19. Materials being characterized include woven, braided, knitted, and stitched fiber architectures. Most of the tests conducted to date have focused on in-plane mechanical properties and impact damage tolerance. A limited amount of fatigue tests have been conducted under compression-compression constant amplitude loading. Additional fatigue tests that include tension-tension and tension-compression cyclic loading will be conducted. The test matrix will also be expanded to include bearing and out-of-plane strength. Structural element level tests such as crippling, stiffener pull-off, and panel buckling will be expanded in the near future. Special fixtures and load introduction techniques will be developed as necessary. These tests will provide preliminary design properties and a database for comparison with analytical models.

- **Objectives**
 - **Develop experimental data base to characterize the mechanical behavior and damage tolerance of selected textile architectures**
 - **Develop preliminary design properties to support design of selected structural elements and subcomponents**
- **Program elements**
 - **In-plane mechanical properties data base for woven, braided and knitted/stitched composites**
 - **Out-of-plane strength and delamination resistance**
 - **Impact damage tolerance and notch effects**
 - **Bearing/mechanical fasteners**
 - **Tension and compression fatigue response**
 - **Preliminary design properties for specific structural elements and subcomponents**

Figure 19

TEST SPECIMENS

The test specimens that are currently being used in the NASA Langley in-house test program are shown in figure 20. The specimens have a nominal thickness of 0.250-inch with length and width as indicated in the sketches. Test results obtained to date indicate that strain gages must be selected to match particular fiber architectures. Factors such as tow size, tow spacing, and textile unit cell dimensions must be accounted for in making strain measurements. For example, a material braided with 3K tows will have a smaller unit cell than a material braided with 12K tows. The local strain response of these materials may be different, and different size strain gages may be required to accurately measure material response. Strain gages that are located directly over a through-the-thickness stitch could be affected by local material response. The size and location of resin pockets could also affect local material response. Additional research on development of standard test methods for textiles will be discussed in a subsequent figure.

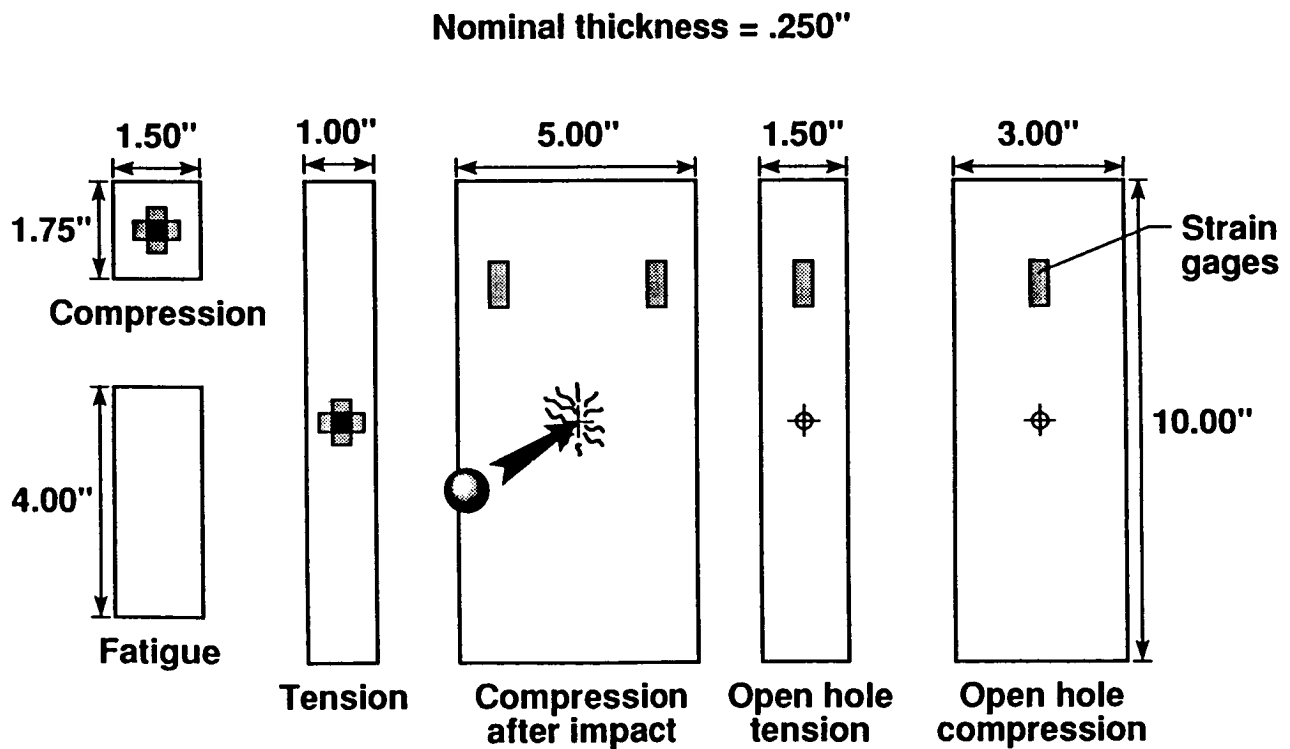


Figure 20

COMPRESSION AND COMPRESSION-AFTER-IMPACT STRENGTH OF QUASI-ISOTROPIC AS4/EPOXY LAMINATES TESTED IN THE 0° DIRECTION

Compression and compression-after-impact (CAI) strengths of knitted/stitched composites are compared with those of laminated composites fabricated with prepreg tape, figure 21. The knitted/stitched fabrics were infiltrated with three different resin systems: Hercules 3501-6, British Petroleum E905L, and 3M PR500. The prepreg tape was fabricated with Hercules 3501-6 epoxy resin. The knitted fabric was produced by knitting four layers of AS4 carbon fibers together with a 70 denier polyester yarn. The knitted subgroups were stacked to form a 16-ply quasi-isotropic (+45, 0, -45, 90)_{2s} preform. The 16-ply preforms were subsequently stitched together with a carbon stitching yarn using a modified lock stitch. The knitted/stitched fabric was produced by Hexcel Hi-Tech.

Test results indicate that the knitting/stitching process reduced the compression strength of the fabric by 25 to 30 percent compared to prepreg tape laminates. However, the major benefits of knitting and stitching are in delamination suppression and damage tolerance. The results shown in figure 21 for a 30 ft.-lb. impact indicate the benefits of through-the-thickness reinforcement. The compression strength for the prepreg tape laminate was reduced from 80 ksi to below 20 ksi as a result of the impact. However, a 150 percent improvement in CAI strength was achieved with the knitted/stitched fabric compared to the prepreg tape laminate. Additional research is underway to identify fiber damage mechanisms due to knitting/stitching so the fabrication process can be optimized to minimize fiber damage and resultant strength loss.

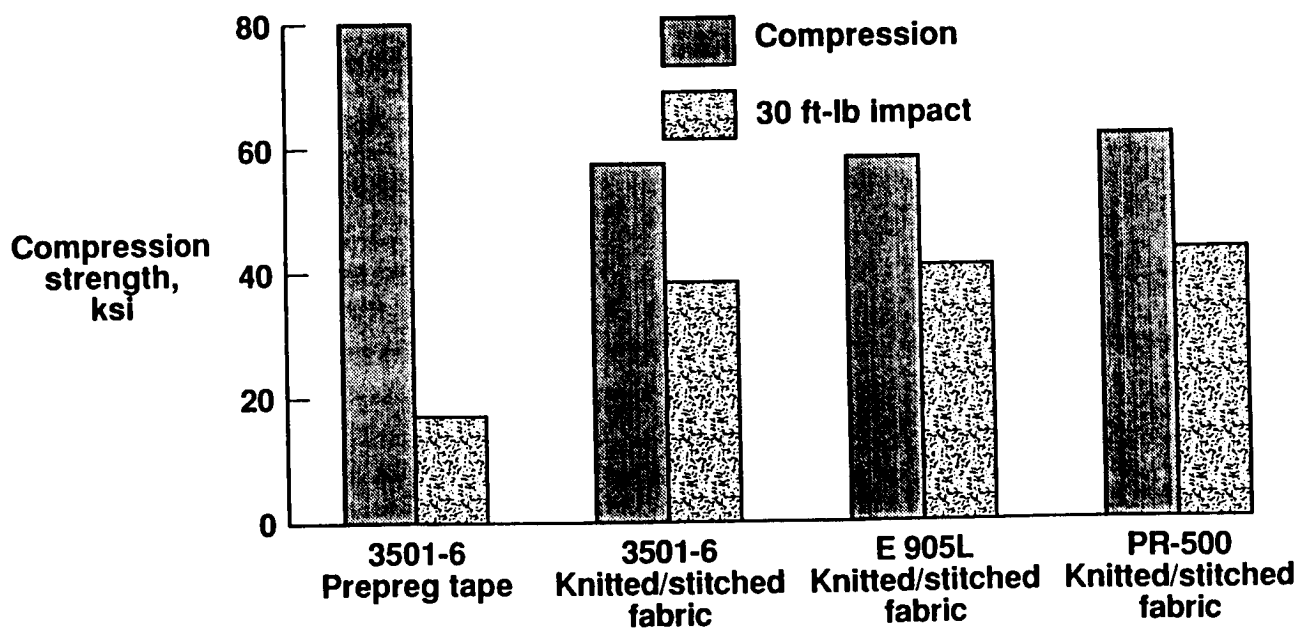


Figure 21

COMPRESSION AND COMPRESSION-AFTER-IMPACT STRENGTH OF BRAIDED COMPOSITE PANELS TESTED IN THE 0° DIRECTION

Compression and compression-after-impact (CAI) strengths of 2-D braided, 2-D braided/stitched, and 3-D braided composites are compared in figure 22. The braided preforms were fabricated with AS4 carbon fibers with a ($\pm 30/0$) fiber architecture. The preforms were infiltrated with British Petroleum E905L epoxy. An impact energy of 30 ft.-lb. was used to impact the panels, which had nominal thicknesses of 0.24-inch.

Test results indicate that the 3-D braided panels had the highest undamaged strength, over 60 ksi, whereas the 2-D braided/stitched panels had the highest CAI strength, over 40 ksi. It is somewhat surprising that the CAI strength for the 3-D braided panels was only slightly better than the CAI strength for the 2-D braided panels which have no through-the-thickness reinforcement. Additional testing is underway to further understand the behavior of braided materials.

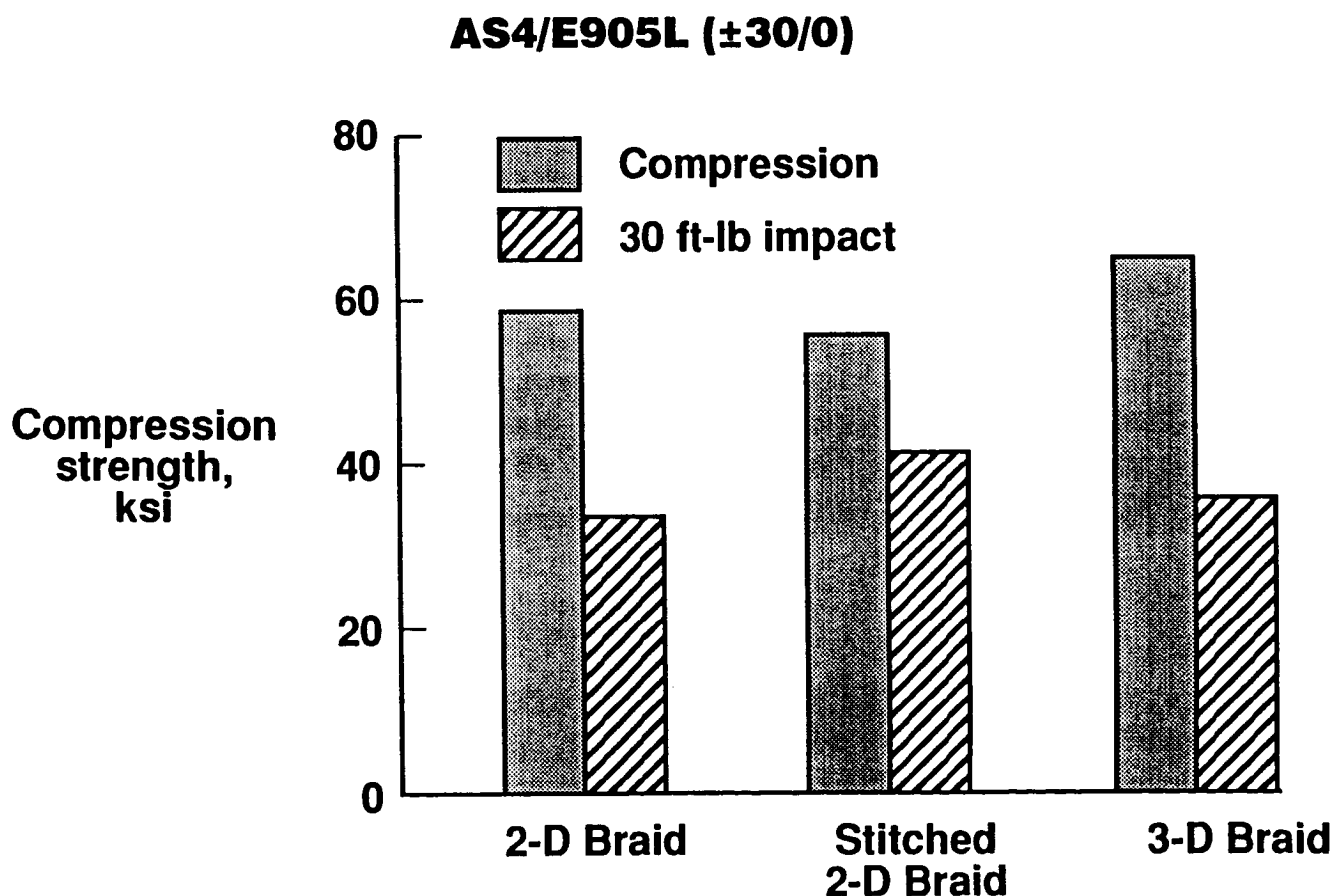


Figure 22

STANDARD TEST METHODS FOR TEXTILES

New test techniques will be required to characterize some of the unique properties of textile reinforced composites. The sketches shown in figure 23 indicate some of the types of tests that must be conducted to explore the benefits of textile material forms. Some of the currently used in-plane test methods may be adequate for textile materials. However, modification of specimen dimensions and strain measurement techniques may be required for some textile architectures. The effect of textile unit cell dimensions on mechanical behavior must be characterized. Since textile materials with through-the-thickness reinforcement offer significant improvement in out-of-plane load capability, adequate test methods must be developed to assess performance improvements. Subelement level tests such as stiffener pull-off must also be developed. Analytical studies, in conjunction with experiments, must be performed to assure that stress states are understood and that local effects are representative of global material response. Available standard test methods in the composites industry will be investigated and used where appropriate.

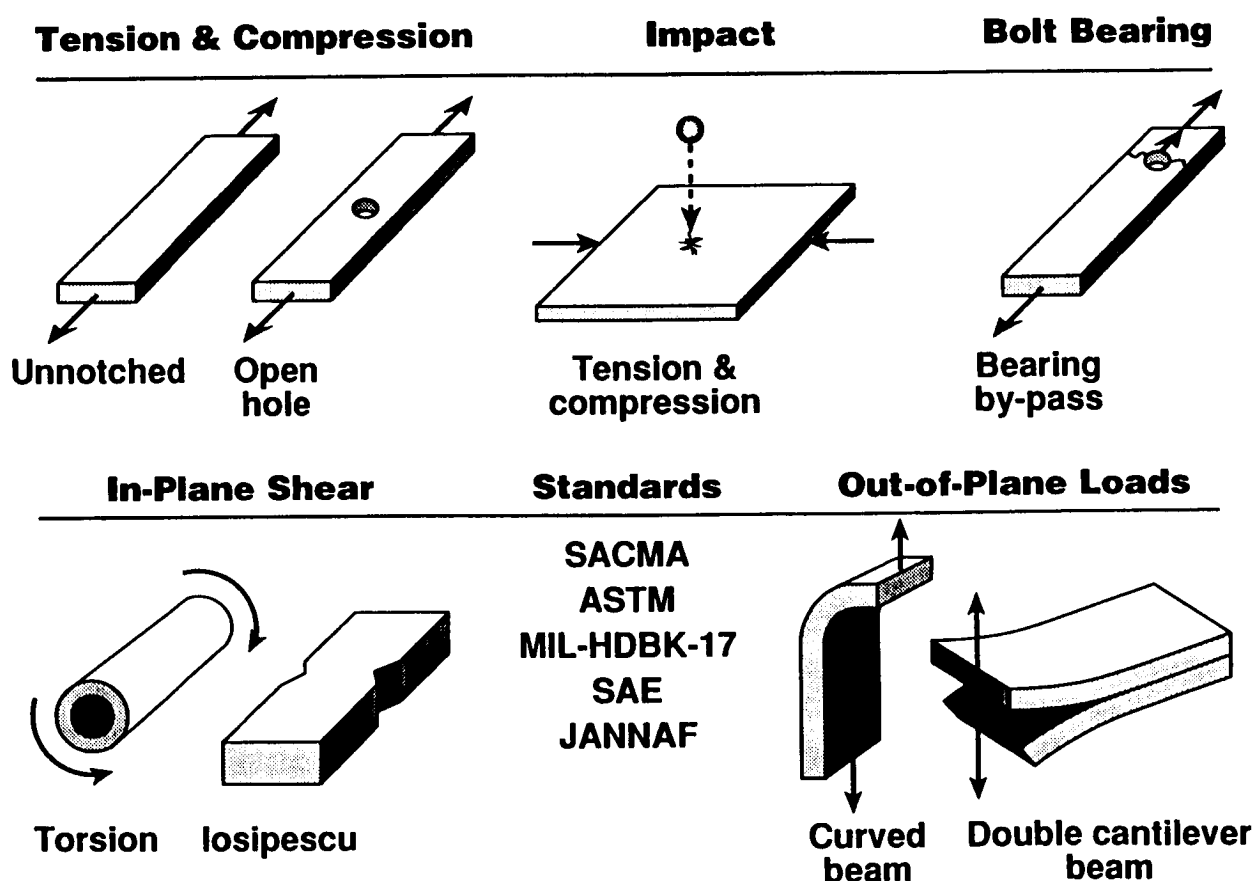


Figure 23

AIRCRAFT FLUIDS EXPOSURE OF RTM COMPOSITES

As part of the resin selection process for resin transfer molding (RTM) of textile materials, Boeing Aerospace is conducting aircraft fluids exposure of several composite systems. The materials that are being evaluated, specimen types, and fluid exposure conditions are indicated in figure 24. Five different resins with AS4 uniweave fabric were selected for the initial test program. The selected exposure conditions and fluids are as follows: (1) 160°F water, (2) room temperature (RT) JP-4 jet fuel, (3) 160°F hydraulic fluid, (4) 160°F turbine oil, (5) RT MEK, (6) RT methylene chloride, and (7) RT deicing fluid. These fluids are representative of those that composite materials may be exposed to during realistic aircraft operational service. Tension (+45/-45)_{2s} and short beam shear (0)_{16s} test specimens were selected to represent matrix dominant failure modes. Room temperature and 180°F test temperatures were selected. Test results are incomplete at this time but should be available in the latter part of calendar year 1991.

14 Day Exposure

<u>Composite Systems</u>	<u>Fluids - Exposure Conditions</u>
• AS4/Hercules 3501-6	• Water - 160°F
• AS4/Shell 862	• JP-4 Jet fuel - RT
• AS4/BP E905L	• Hydraulic fluid - 160°F
• AS4/Dow CET-2	• Turbine oil - 160°F
• AS4/Ciba Geigy 5292	• MEK - RT
	• Methylene chloride - RT
	• Deicing fluid - RT
<u>Test Specimens/Conditions</u>	
• (+45/-45) _{2s} Tension	
• (0) _{16s} Short beam shear	
• Room temperature	
• 180°F	

Figure 24

EFFECTS OF MOISTURE AND TEMPERATURE ON RTM COMPOSITES

Results from hot/wet compression tests conducted at NASA Langley on six different RTM composite material systems are presented in figure 25. Since different fabric architectures were used in the six materials, strength retention results are compared to their respective room temperature baseline strength. The specimens were soaked in a 160°F water bath in an air circulating oven for 45 days prior to testing. After exposure, the specimens were tested at 180°F. The best performance was achieved with Dow CET-2 and 3M PR 500 resins, a strength loss of only 15 percent. The Shell 862/763 resin lost about 35 percent in strength due to hot/wet exposure. Additional tests will be conducted on emerging resins as they become available for RTM processing studies.

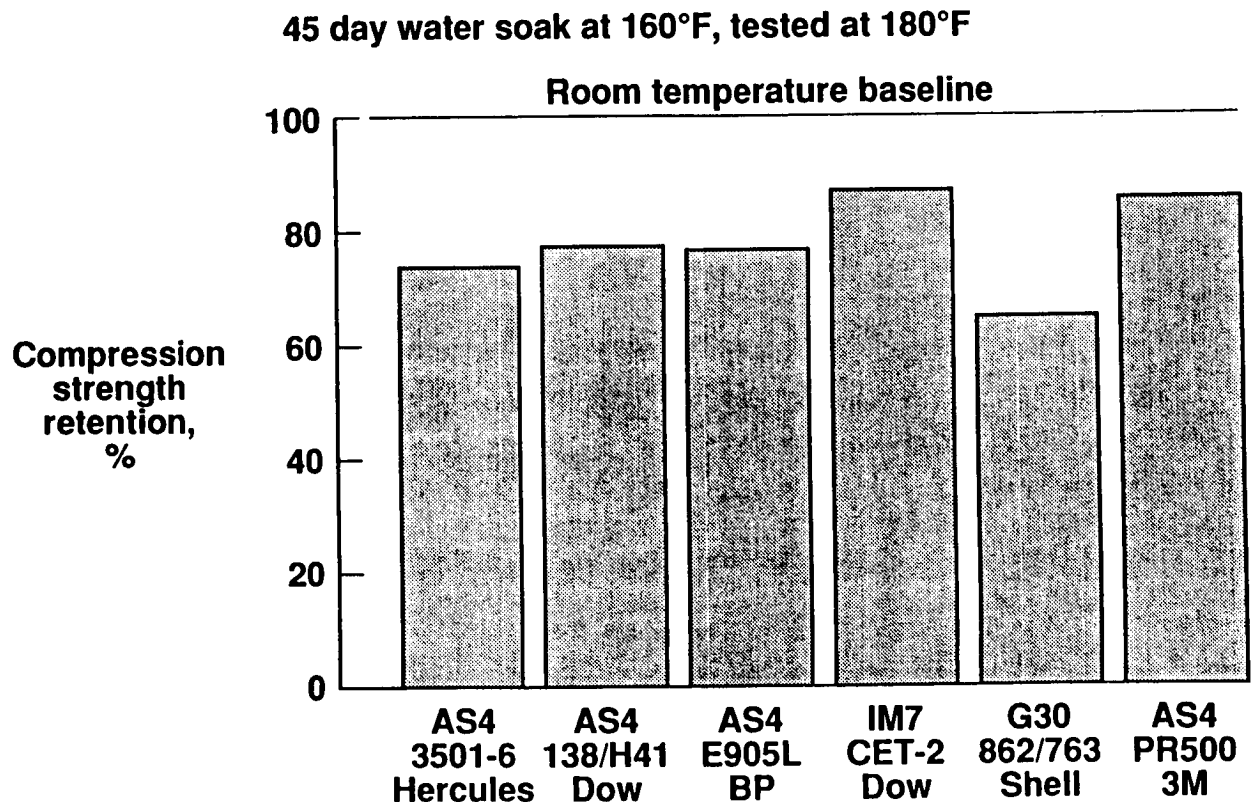


Figure 25

TEXTILE REINFORCED COMPOSITE STRUCTURAL SUBCOMPONENTS

As part of the redirection of the Lockheed and Grumman ACT contracts, specific fuselage subcomponents were selected as candidates for application of textile material forms. Based on discussions between NASA Langley, Lockheed, Grumman, and Boeing, the four subcomponents shown in figure 26 were selected. These structural subcomponents were selected to exploit damage tolerance and through-the-thickness strength capability of textile materials. Structural tests will be conducted on each structural subcomponent to verify the performance of textile architectures. Analytical predictions will be performed and results will be correlated with experimental behavior.

Particular design issues associated with each subcomponent are indicated in figure 26. It is anticipated that several textile processes such as integral weaving, braiding, knitting, and stitching will be used to produce near net-shaped structural subcomponents. Some obvious candidates include continuously braided circumferential frames, integrally woven stiffened panels, and stitched reinforcement around window openings. An integrated design-build-team effort will be conducted by Boeing, Lockheed, and Grumman. This is necessary since some of the subcomponents will be delivered to Boeing for test in their fixtures. Additional test articles will be delivered to NASA Langley for testing in new combined load machines/fixtures that are under development.

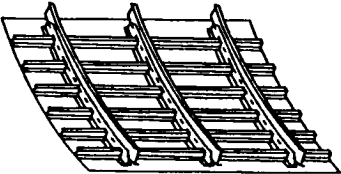
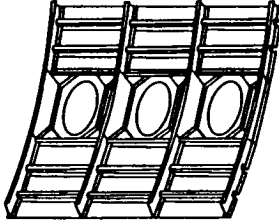
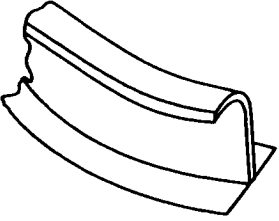
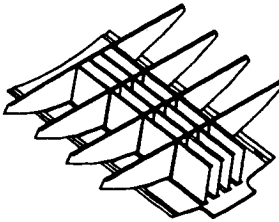
Skin/Stiffened Fuselage Panels  • Damage tolerance • Buckling/postbuckling • Pressure pillowing • Combined cyclic loads	Fuselage Window Belt  • Out-of-plane/interlaminar stresses • Stability under combined loads • Damage tolerance/pressure containment
Circumferential Fuselage Frames  • Combined loads • High interlaminar stresses • Durability of frame/stringer/skin attachments • Frame splices	Keel Beam/Frame Intersections  • Impact damage tolerance • Through penetration/damage containment • Durability of beam/frame splices

Figure 26

STRUCTURAL ELEMENT AND SUBCOMPONENT EVALUATION

Key structural element and subcomponent tests must be conducted to assess performance of textile reinforced composites. Tests that measure out-of-plane load capability and damage tolerance are required to demonstrate the attributes of textile material forms. Some of the tests that are planned by the NASA ACT contractors are shown in figure 27. It is expected that textile reinforced composite structural elements will demonstrate significant improvements in compression and shear postbuckling strength, post-impact compression strength, and combined compression and shear load capability. Analytical methods will be developed to predict structural response. Predicted behavior will be compared with experimental results.

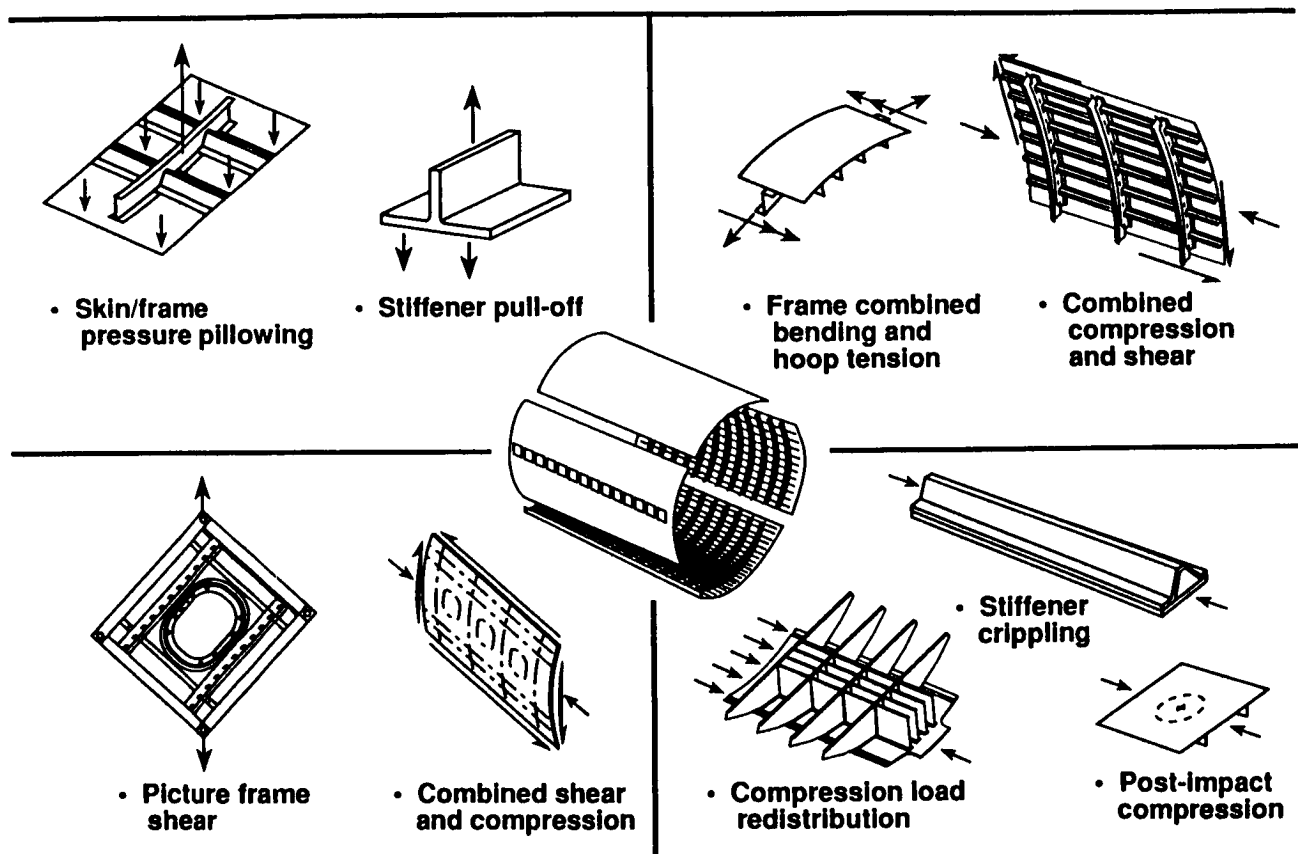


Figure 27

NEAR-TERM RESEARCH DIRECTIONS

Redirection of some of the NASA ACT contracts on textile reinforced composites has provided an aircraft structures focus to the textile program. This focus will allow textiles to be applied to specific structural elements where textiles offer a clear advantage over more conventional material forms. The near-term research directions for the NASA Langley textile reinforced composites program are indicated in figure 28. Engineering design guidelines and performance requirements for application of textile to aircraft structures will be established. Analytical models will be developed to predict material behavior and structural performance.

Processing and fabrication studies that focus on science-based understanding of processing parameters and tooling concepts will be accelerated. Trial-and-error processing studies that have been conducted in the past are too costly and must be minimized. New test methods are required to establish an accurate assessment of textile material performance. Design property databases for applicable textile material forms must be generated so that designers can conduct accurate trade studies.

Structural elements and subcomponents that exploit the full potential of textile material forms will be designed, fabricated, and tested. An integrated team that includes textile preformers, structural designers, analysts, process engineers, and tool designers has been established to work together for cost-effective structural application of textile materials.

- **Establish engineering design guidelines and performance requirements for aircraft applications**
- **Develop analytical models to predict material behavior and structural performance**
- **Develop science-based processing/fabrication methods for aircraft-quality structures**
- **Expand design property data base for most promising material forms**
- **Design, fabricate, test and analyze structural elements that exploit properties of textile material forms**

Figure 28